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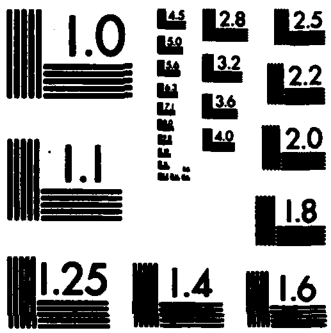
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AD-A133 064

FINAL REPORT

Title: THE DEPENDENCE OF THE RADAR MODULATION TRANSFER FUNCTION ON ENVIRONMENTAL CONDITIONS AND WAVE PARAMETERS
(A contribution to studies of radar backscattering from the sea surface)

Author: Dr. David E. Weissman

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report shows how the Modulation Transfer Function (MTF), an important quantity for remote sensing of ocean wave spectra, will vary with environmental conditions that control the air-sea interaction. The accuracy with which this quantity is known will determine the quality of remote measurements of ocean wave spectra. Microwave remote sensing of individual ocean wavelengths (and the complete directional spectrum) is based on synchronized reflect-

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Recent measurements by the Naval Research Laboratory of the ocean wave-radar modulation transfer function from fixed ocean platforms, over a period of several years, have demonstrated that the local hydrodynamic modulation of short centimeter waves is affected by the air-sea interaction. Results from widely separated ocean regions also show different individual properties, that make detailed measurements necessary. An X-band radar with vertical polarization was mounted on a platform in the Gulf of Mexico during Nov.-Dec. 1978. The data set is computer stored and was processed by the Naval Research Laboratroy, Washington, D.C. A selective study of this data has been conducted on the separate independent influence of wind speed, air-sea temperature difference and wave slope on the MTF and the average radar cross section. Dependence on all these parameters was observed. Data from other experiments agree with these results. Variations of the coherence function for the MTF imply that other mechanisms must be found for these modulation effects other than hydrodynamic (wave-wave) interactions. An important conclusion of this study is that the surface stress depends not only on the wind speed, but also on air-sea temperature difference and wave slope.

ABSTRACT

This report shows how the Modulation Transfer Function, an important quantity for remote microwave sensing of ocean wave spectra, will vary with environmental conditions that control the air-sea interaction. The accuracy with which this quantity is known will determine the quality of remote measurements of ocean wave spectra. Microwave remote sensing of individual ocean wavelengths (and the complete directional spectrum) is based on synchronized reflectivity variations along each wave, that the radar can resolve spatially. This study demonstrates that the MTF, which is the ratio of this reflectivity (amplitude of variation) to the ocean wave amplitude, is affected by the air-sea interaction, in addition to the hydrodynamic interaction between capillary and long gravity waves.

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hydrodynamic (wave-wave) interactions. An important conclusion of this study is that the surface stress depends not only on the wind speed, but also on air-sea temperature difference and wave slope.

INTRODUCTION

Microwave radar signals (wavelength about 3 cm) obliquely incident on the ocean surface encounters a very rough surface that scatters this energy in all directions. At steep angles, backscattered signals are controlled by matching "Bragg-waves" that are in the short gravity-capillary part of the surface spectrum. The reflectivity of patches of these scatterers and their synchronous variation along a large gravity wave permits the spatial resolution of the ocean wavelength by the radar. This reflectivity (local radar cross section) oscillates along the large wave because its orbital velocity modulates the short gravity and capillary waves. Thinking in terms of a simple linear system model, where the output is the amplitude (and phase, relative to the wave peak) of the local radar cross section cycle, the MTF behaves like the "gain" of this system, with the input being one of the long ocean gravity waves. Since the remote sensing problem is to infer the amplitude of each long "input" gravity wave, based on the intensity of the observed radar cross section variation, the MTF mus be known or estimated to invert this measurement. Higher values of the MTF make ocean waves more visible to a radar (either "Wave Spectrometers" or imaging radars), lower values mean a lower "visibility" that may not be detectable, or accurately measureable.

Previous studies (Plant, et. al 1983; Wright et. al., 1980; Valenzuela &Wright, 1979; Keller & Wright, 1975) have provided the theoretical and experimental foundation for the understanding of the modulation transfer function. Tower based L-band and X-band measurements have shown the fundamental properties of the MTF within the ocean wave spectrum and as a function of the environment: wind and wave parameters. This study presents important progress in the understanding of the dependence of the MTF on the environmental conditions at the air-sea interface and on the effect of the wave height/slope on this function. This is possible because of a favorable range of weather and wave conditions during the measurement period that permitted comparison of the MTF within this large dynamic range of parameters.

The measurement was conducted from an oceanographic tower known as Stage I, operated by the Naval Coastal Systems Laboratory near Panama City, Florida (Fig. 1). This tower functions as a residence and research facility with living accomodations and support facilities. This platform, located 12 miles offshore in 32 meters of water, is 32 meters square and about 18 meters above the surface. The ocean bottom slope was small: 0.001. The measurements reported here were conducted during December 1978. This experiment was conceived and initiated by the late Dr. John (Jack) W. Wright of NRL. The field and data processing activities were completed by William C. Keller and Dr. William J. Plant.

Throughout the period of observation, winds, scattering coefficient, sea surface and air temperature, wave height, and other meteorological variables were recorded (Niziol and Mack, 1979). Measurements of true wind speed and direction were made at the 24.7 m height with a Beckman-Whitley wind system. Data on wind speed and

direction were continuously recorded. Sea surface temperature and air temperatures at the 24.7m, 9.3m, and 4.4m height were continuously monitored with calibrated Foxboro thermistors. The ocean wave trough, crest and average wave height were computed and tabulated hourly.

Some comparisons will be made to the results obtained during the West Coast experiment (Wright et. al., 1980) conducted in 1976 and the MARSEN experiment conducted in 1979 (Plant, et. al. 1983).

ENVIRONMENTAL CONDITIONS AND DATA ANALYSIS

Environmental conditions during the period of observation were very variable. Winds ranged from 5 to 15 meters/sec. More important was the air temperature variation; from a minimum of 2 deg. C up to 24 deg. C. Since the sea temperature stayed between 20 and 22 deg. C, both stable and unstable conditions were encountered. In addition to the physical variables, the wave height and slope were also considered as parameters in this study. The rms wave heights ranged from 0.2 to 2.2 meters, and the rms slope up to about 0.06. Approximately 100 hours of experiment data were recorded.

The X-band (9.3 GHz) radar was mounted on a movable platform so that it could be positioned at any chosen look direction. The grazing (depression) angle was 45 degrees for all the data taken. The coherent (CW) radar techniques used to acquire the AM and FM parts of the backscattered signal are discussed in a recent paper by Plant, et.al. (1983). The AM channel was squared in an analog multiplier and low pass filtered at 1 Hz to give the received power. The FM channel contains Doppler and hence velocity information: it yielded long wave orbital velocity and height spectra. The statistical signal processing and correlation techniques to determine the modulation transfer function are also discussed fully in this paper. The coherence function was also computed, and proved to be an important quantity in the interpretation of the data under the wide range of conditions encountered. This function denotes the amount of control that the large wave orbital velocity has on the reflectivity variations along the waves. Lower values of the coherence

imply other mechanisms are influencing the MTF. The data shows that unstable conditions reduce the coherence, opening the search for other mechanisms that influence the radar backscattering properties.

The data was blocked into 20 minute segments. The ouput functions for these segments are: FM spectra, AM spectra, orbital velocity spectra, wave height spectra, magnitude squared coherence function, magnitude and phase of the modulation transfer function and wind speed. The rms slope and average radar cross section were easily calculable from the FM and AM spectra. These segments were filed in true time sequence, and labeled according to their environmental and wave (height and slope) conditions. In order to search for the MTF dependence on a single parameter, all the files with a chosen, limited range of the other parameters were averaged. Then this parameter was stepped through a sequence of values. For example, in the case of wind speed dependence the MTF vs. frequency was computed from all (either stable or unstable) records having wind speeds of 4-6, 6-8, 8-10, and 10-12 m/s respectively. (See Fig. 2 and 3 .) Then for a given surface frequency (and wave length) the MTF variation with wind speed could be estimated.

EFFECTS RELATED TO ENVIRONMENTAL PARAMETERS

The analysis of the MTF data shows that it is affected by both wind speed and air-sea temperature difference. In addition, it is also affected by the wave parameters; the rms slope. For purposes

of discussion, a functional representation of the magnitude of "m" could be written:

$$|m| = f\ (U, \Delta T, \mathrm{sqr}[\langle s^2 \rangle]\ )$$

The data analysis in this report will provide some empirical results which demonstrates the size and rates of change of this function with respect to these variables. Because of the complex influence of all of these parameters, the dependence on any one must be qualified with respect to the values of the other variables. The strongest dependence is that on the wind speed. Figure (2) shows the decrease on the MTF of 25 meter waves for both stable and unstable conditions. The results here represent an average over all values of wave height. Each data point represents an average over 2 meter/sec range of winds, and is positioned at the center of that range. The "stable" data includes all measurements in the range of temperature difference (air-sea temperatures) of -5 to +5 deg. C. The "unstable data set (including all data within the temperature differential range of -20 to -5 deg.) displays a marked decrease in the magnitude of the MTF, at each corresponding wind speed. Both of these groups of data display a good fit to an inverse wind speed curve. Approximate formulas based on a "best fit" to a power law function are (with a coefficient of determination - "quality of fit" index of above 0.9):

STABLE CONDITION: $|m| = 82/U$ $\qquad 5 \le U \le 9$ M/s

UNSTABLE CONDITION: $|m| = 49/U$ $\qquad 7 \le U \le 11$ M/s

Two significant points are obvious from this result. The first is that the MTF decreases by a factor of 1.7 for unstable conditions, at all wind speeds. The second is that regardless of the temperature state of the air-sea interface, the MTF is inversely proportional to the wind speed. Therefore while the principal influence on the MTF is the wave orbital velocity, the wind speed has a moderating effect on its magnitude. Also noted in the data was the coherence function, of the wave frequency. This was usually in the range of 0.4 to 0.6, but excursions beyond these limits also (Fig.10) occurred. This range of values is consistent with an external mechanism (in addition to the orbital velocity) affecting the local roughness and radar reflectivity. Further support for this comes from comparing stable and unstable cases. The unstable condition almost always reduces the coherence function, indicating a more complicated structure (probably turbulent) of the wind profile above the waves. This in turn affects the MTF but in a manner uncorrelated with the orbital velocity. The same observations can be made for the data from the 11 meter waves. Therefore it is a reasonable assumption that these effects apply to a large part of the surface spectrum. Data for a look direction of 45 deg. with respect to the wind shows similar environmental effects, but the level of the magnitude does decrease as this azimuthal angle changes. The strength of these effects are strongly influenced by the wave height and slope. This aspect will be further addressed in the following section.

The average of the radar cross section measured from a tower taken over a long time interval, much longer than the wave period,

yields a measure of the average surface roughness, and is proportional to the radar cross section measured from an aircraft or satellite with a Scatterometer. (Schroeder, et. al. 1982) For X-band, the wind speed dependence has been chosen to be strong, but considerable variation and data spread is always observed when wind speed is used as the independent variable. The results in this study provide an excellent opportunity to observe the role of air-sea temperature difference on the radar cross section. If the possible role of wave height is ignored (results include the entire range of wave heights and slopes), then the wind speed dependence can be grouped into two sets, as show in Fig. 4 . The data points associated with the unstable conditions exhibit a higher radar cross section at all winds, by several dB, in most cases. The empirical conclusion is that unstable conditions increase the surface stress beyond the neutral value at a given wind.

The important implication, from an applications viewpoint, is that an electromagnetic sensor of this type, that is being developed to remotely measure surface winds will give a more precise result if the air-sea temperature difference is known and included in the algorithms used to invert the backscattered power. In addition, wave slope has also been observed to have a strong influence on the radar cross section. Therefore slope must be treated as another independent variable, along with wind speed and temperature in modeling the backscatter response.

EFFECTS RELATED TO WAVE PARAMETERS

Earlier aircraft based measurements of the dependence of the radar cross section on the air-sea interaction (Krishen, Jones & Ross) presumed that, like the classical steady state spectrum models, there is a one-to-one relationship between wind speed and wave height (and slope) so that only wind speed parameterization is necessary. However, actual ocean conditions usually do not satisfy this assumption. Depending on fetch, wind direction and duration, and remote sources of waves, there is a wide range of possible wave heights (and slopes) at a given wind speed. The data analysis in this study demonstrates that both modulation transfer function and radar cross section results have a definite dependence on wave slope when the other parameters can be kept within a narrow range. Also important is the fact that these dependencies: on wave slope, wind speed, and air-sea temperature difference, are not "separable". Unstable air temperature conditions produce very different dependencies on the wave slope and wind speed than do stable conditions. Circumstances during the Gulf of Mexico experiment were very fortuitous in that a wide range and mixture of conditions influenced the RCS and MTF data.

Fig. 5 and 6 show the effects of these conditions on the MTF of 0.25Hz (25 meter) and 0.375Hz (11 meter) waves. For near neutral ($-5 < T < +5$ deg. C) conditions and winds equal to or above 6 m/s, the MTF is shown to display a strong inverse RMS slope dependence. At the lower wind speeds (4 to 6 m/s) the sensitivity to slope is very weak and does not decrease with slope. Under

unstable conditions the slope dependence is very different. In the 6 to 8 m/s range, changes in the MTF are relatively small compared to the stable case. At the higher wind speed range (8 - 10 m/s), our Gulf of Mexico data shows that the MTF increases steeply with slope, just the opposite of the stable case behavior. Fig. 7 shows results from a similar experimental configuration, the West Coast Experiment, during Feb.-March, 1977 (see Wright et.al. 1980). This data cannot be easily separated into narrow air-sea temperature ranges because only wind speed was carefully monitored. At that time, the importance of air-sea temperature was not known. It is possible that during the course of this MTF experiment, the air-sea temperature differences varied considerably and were really a mixture of near neutral and unstable conditions. Studying these MTF results, only those for the 4 - 5 m/s and 9 - 10 m/s ranges are comparable (decrease with slope) to the stable Gulf of Mexico results. Most of the other data displays an increase in magnitude with increasing slope. This is similar to the unstable GM results, but no firm conclusions can be drawn because of the unknown air temperature values.

Another discovery of this data analysis is the strong dependence of the radar cross section on the wave slope, at a given wind speed. The stable and unstable data of Figs. 5 & 6 were reorganized into wind speed ranges; 6 - 7, 7 - 8, etc. and the RMS wave slope was used as a parameter for the average backscattered power (uncalibrated radar cross

section). The results of this investigation can be seen in Figs. 8 & 9. In the former, the stable condition results in a strong dependence on RMS slope, especially in the 7-8 and 9-10 M/s bands. Also seen in Fig. 8 is the expected increase with wind, when the slope is held constant. The unstable condition results in an opposite slope sensitivity. Most of the data of Fig. 9 shows a decrease in the RCS with slope. Although there are only 3 or 4 data points at the 6-7 and 7-8 M/s condition, the trend is unmistakeably down. These results are very significant in the development of accurate algorithms to measure air-sea conditions and parameters from airborne backscatter data. Future flight measurement programs should be influenced by these relationships so that all the important quantities can be observed simultaneously and separated in the data analysis and algorithm development. Previous studies at L-band have also found that the wind speed and directional dependence is affected by the air-sea temperature conditions (Thompson, et. al. 1983).

COHERENCE FUNCTION

The basis for the definition of the MTF is the assumption that the wave orbital velocity is the principal driving mechanism for the reflectivity variations sensed by the microwave radar. This is analogous to a single input-single output linear system. If this model were completely accurate then the measured coherence (Bendat & Piersol, 1971) between the orbital velocity and the backscattered power would be unity. On the contrary the measured values of coherence vary from about 0.25 to 0.7, with the average being about 0.5. As explained by Bendat and Piersol, values of coherence less than unity can be caused

by one or more of the following possible situations:

(a) extraneous "noise" or other sources are present either in the input or output.

(b) the system relating input and output is not linear.

If non-linearity were a strong factor then the spectrum of the amplitude demodulated signal (instantaneous backscattered power) would look much different than the orbital velocity spectrum. But this is not the case: they are similar, usually with the dominant peaks occuring at the same frequency. For the other alternative, the term "noise" or other sources must represent the local wind structure within the waves. Since it is not coherent with the orbital velocity, it must be random i.e. related to the turbulent characteristics of the air-sea interaction (Townsend, 1972).

This point of view will be supported by the results seen in Fig. 10 Realizing that the total modulation (Wright, et.al. 1980, Eq.5) which is the product of the MTF and the wave slope, (U/C), increases, the relative "signal-to-noise" also increases. The coherence values in Fig. 10 for stable conditions show a steadily increasing slope for winds from 4 to 10 M/s. Even though the MTF is seen to decrease in Fig. 5, the product (total modulation, M) is still advancing gradually. The net increase in the total modulation ($|m| \times (U/C)$) as the slope increases from 0.0225 to 0.0575 seems too small to account for the large increase in the coherence alone, in terms of a "signal-to-noise" effect. Another possible effect is that the larger slope influences the wind-boundary layer structure over the waves, in a way that also creates the uncorrelated radar modulation features. Additional support comes from the coherence properties under unstable conditions, seen in the same figure. For slopes below 0.04, the coherence is seen to be low,

less than 0.3, consistent with unstable, turbulent wind conditions. Then as the slope increases, tightening the coupling (average stress) between the mean air flow and the interface, the coherence goes up. The implication is that the turbulence will then have a dimished effect on the reflectivity variations, or perhaps will be correlated with the wave periodicity. These interpretations are only qualitative, and should be explored further with focussed experimental and theoretical studies.

CONCLUSIONS

The quality and technical performance of a radar system observing ocean wave spectra depends on the ability to invert the radar sensed spectra and wave features into ocean wave spectra. An auxiliary knowledge of the MTF is therefore required. These studies in the Gulf of Mexico (X-band, vertical polarization) and other experiments at San Diego and in the North Sea during MARSEN demonstrate that this function can vary over a large dynamic range (6 to 1) and will, in general, depend not only on the wind speed (which had been detected and studied earlier) but also on the air-sea temperature difference and wave slope. In addition, preliminary observations of the radar cross section during this experiment, indicate that it too varies with the wave parameters. Assuming that the local and averaged (time or ensemble) X-band radar cross section depends strongly on the wind stress, these results lead to the significant conclusion that the surface stress imposed by the wind depends not only on the wind speed and air-sea temperature difference, but also on the wave slope. These quantities affect the radar properties in a complicated, interactive way; so that it is difficult

to separate their singular effects through independent measurements. For example, the effect and intensity that the wave slope has depends on whether the air-sea temperature difference is stable (near neutral) or unstable.

Additional measurements at both lower (less than 4 M/s) and higher (greater than 10 M/s) would be very useful in modeling the physical mechanisms behind these results. Previous theoretical studies (Valenzuela and Wright, 1979) have been partially successful in modeling the MTF dependence on wave orbital velocity and slope. However the results based on approximations (up to second order) to a very complex mathematical relation do not predict the strong decrease in the MTF with slope. The opportunity exists for further advances in this area.

The previous detailed study of the West Coast Experiment (Wright, et. al. 1980) noted that wave-wave interactions were not sufficient to interpret the data; it alluded to a stronger source affecting the modulation. The wave-induced airflow was identified as a subject requiring further investigation. This study based on the Gulf of Mexico Experiment has greatly advanced this point-of-view and provided a data base that should be valuable in future modeling and theoretical studies.

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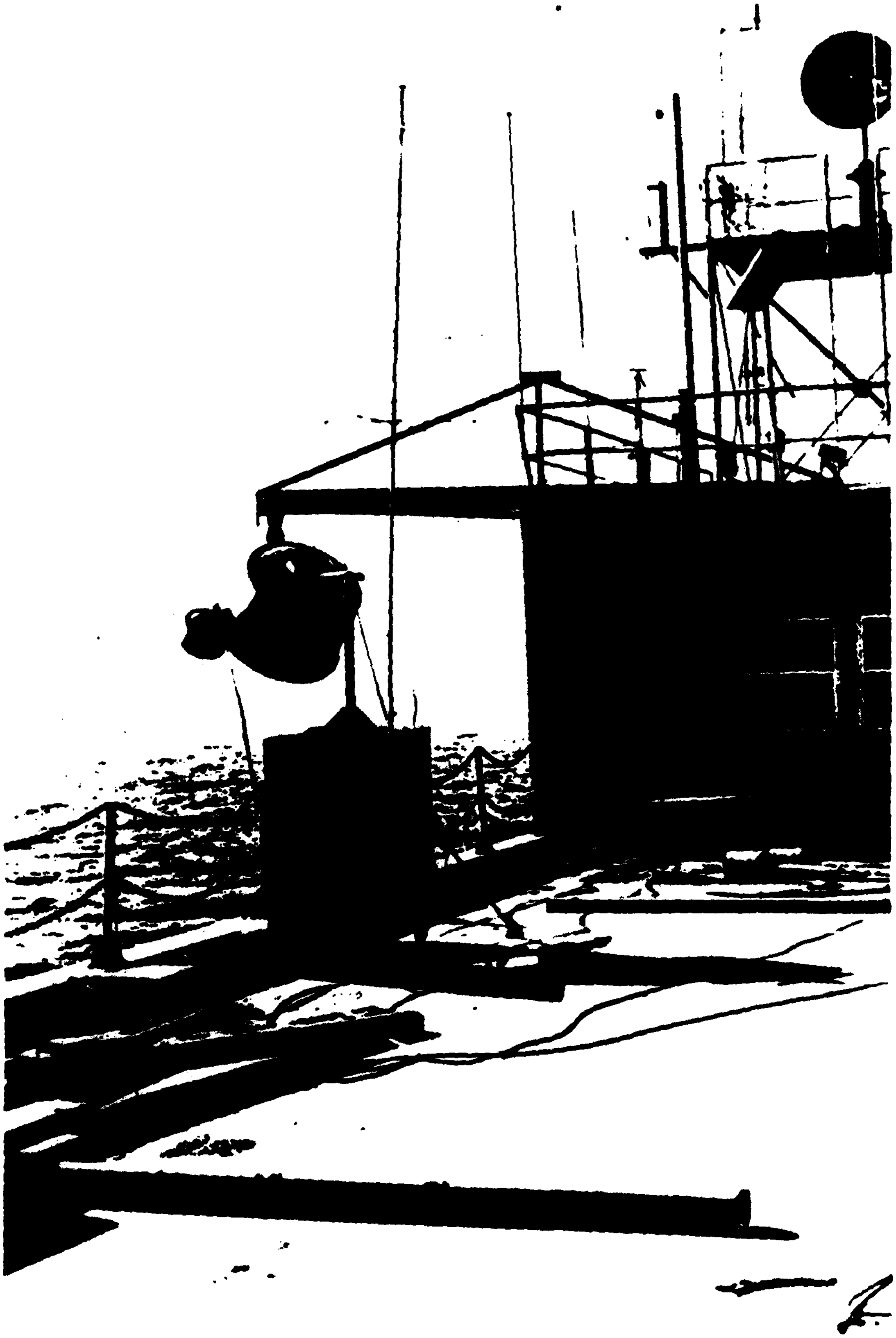

Figure 1

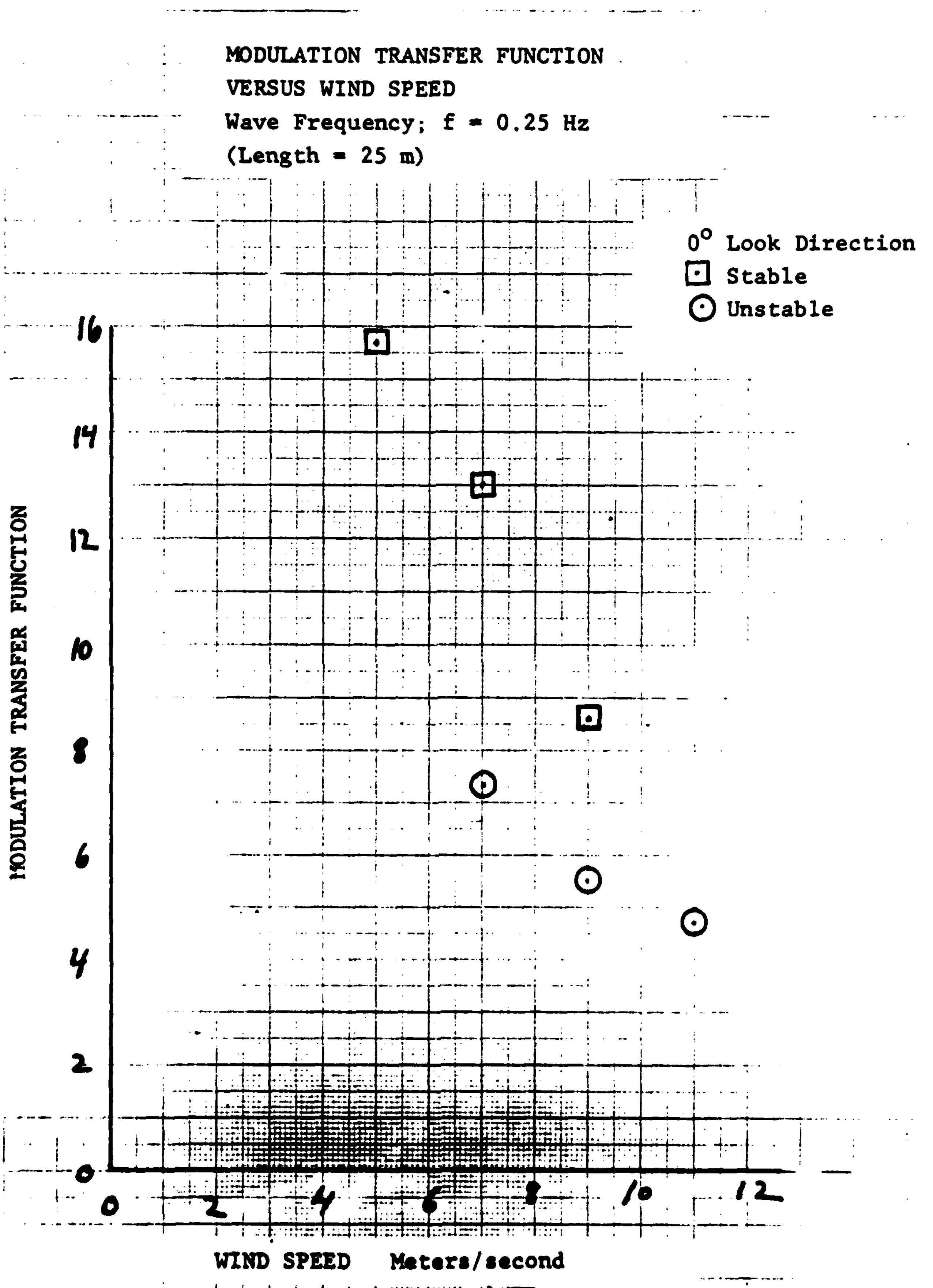

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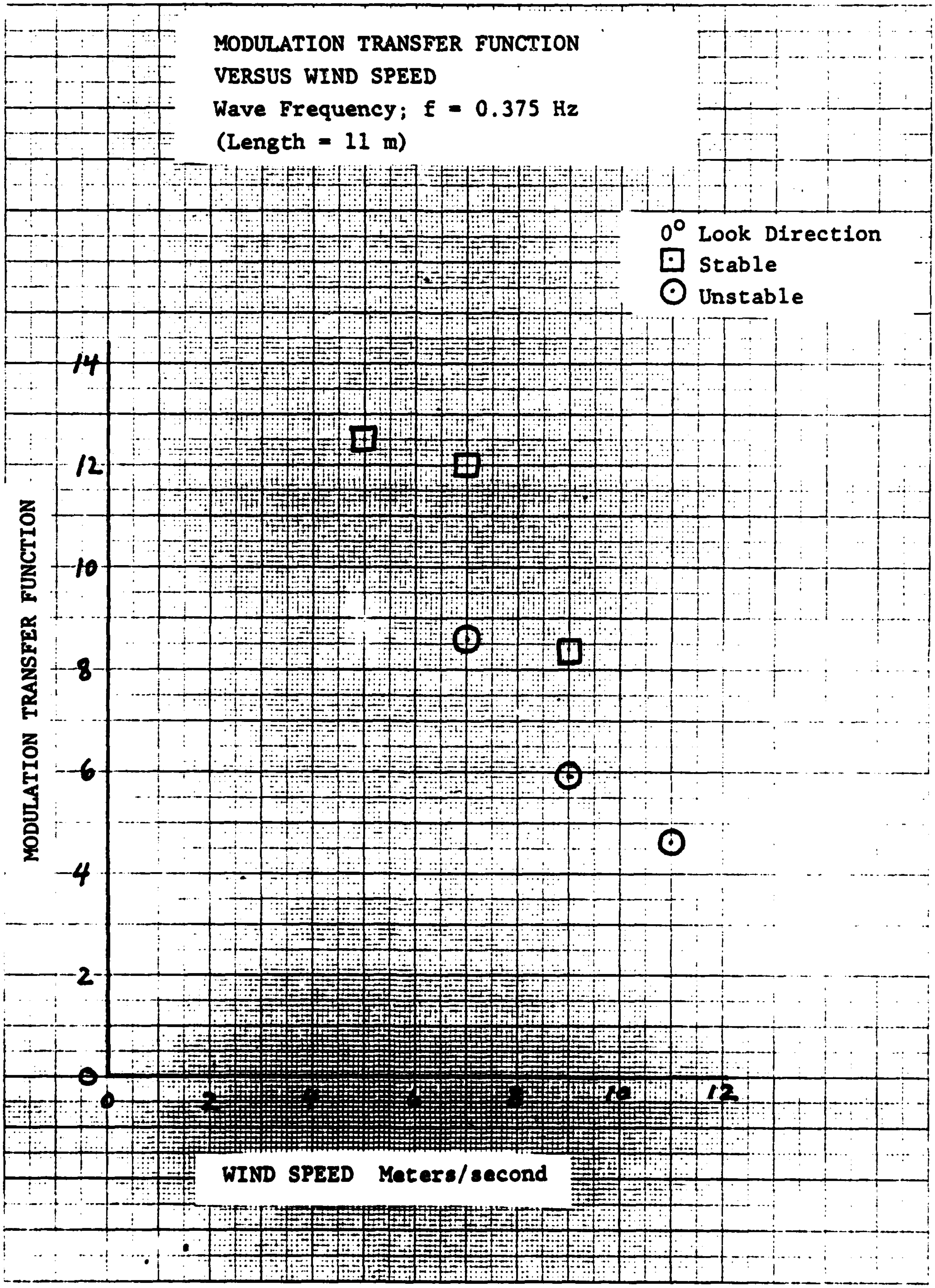
Figure 2



MODULATION TRANSFER FUNCTION
VERSUS WIND SPEED
Wave Frequency; f = 0.375 Hz
(Length = 11 m)
0° Look Direction
Stable
Unstable
MODULATION TRANSFER FUNCTION
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
WIND SPEED Meters/second

Figure 3

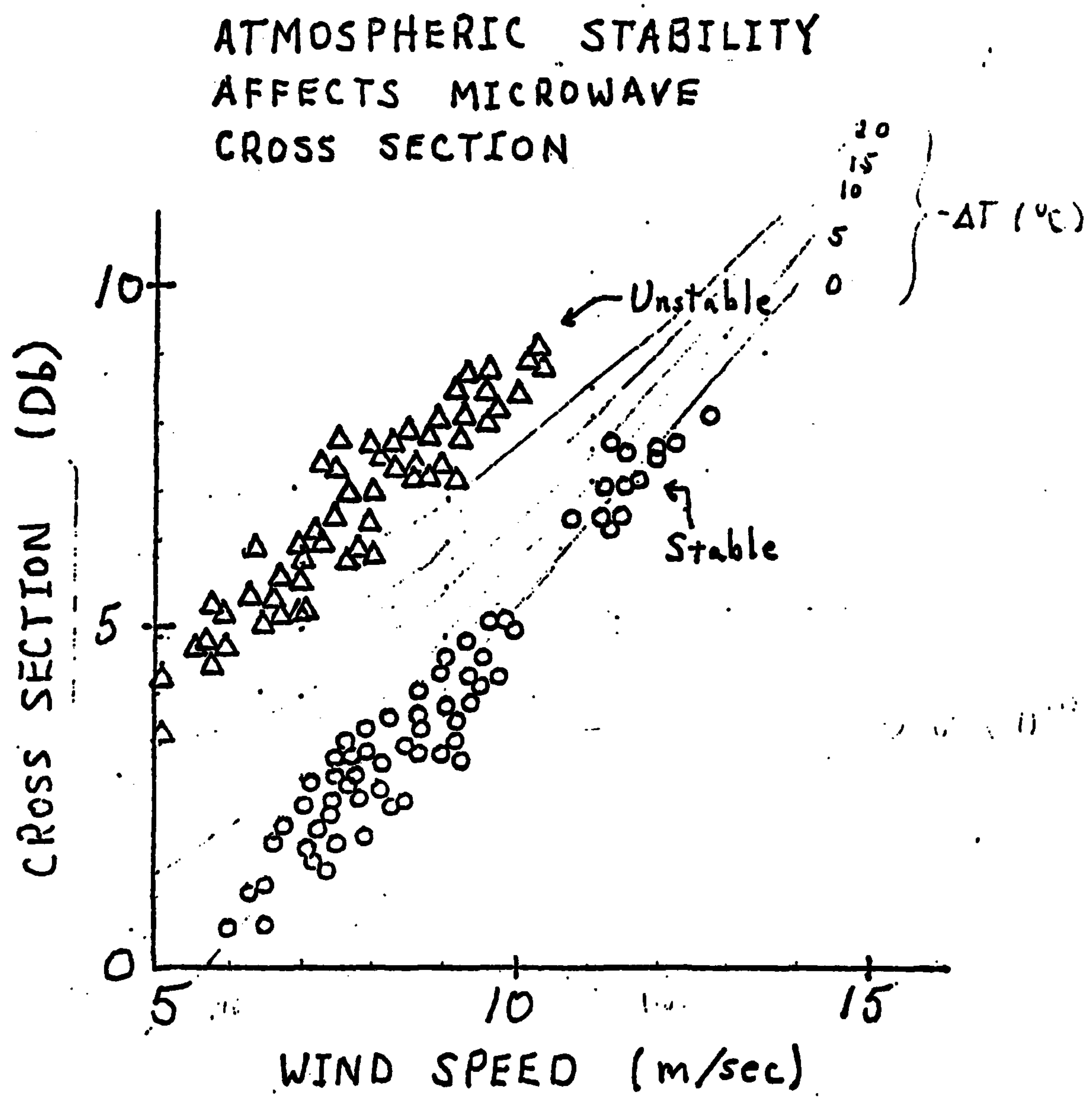

ATMOSPHERIC STABILITY
AFFECTS MICROWAVE
CROSS SECTION
20
15
10
5
0
-ΔT (°C)
Unstable
Stable
10
5
0
CROSS SECTION (Db)
5
10
15
WIND SPEED (m/sec)

Figure 4

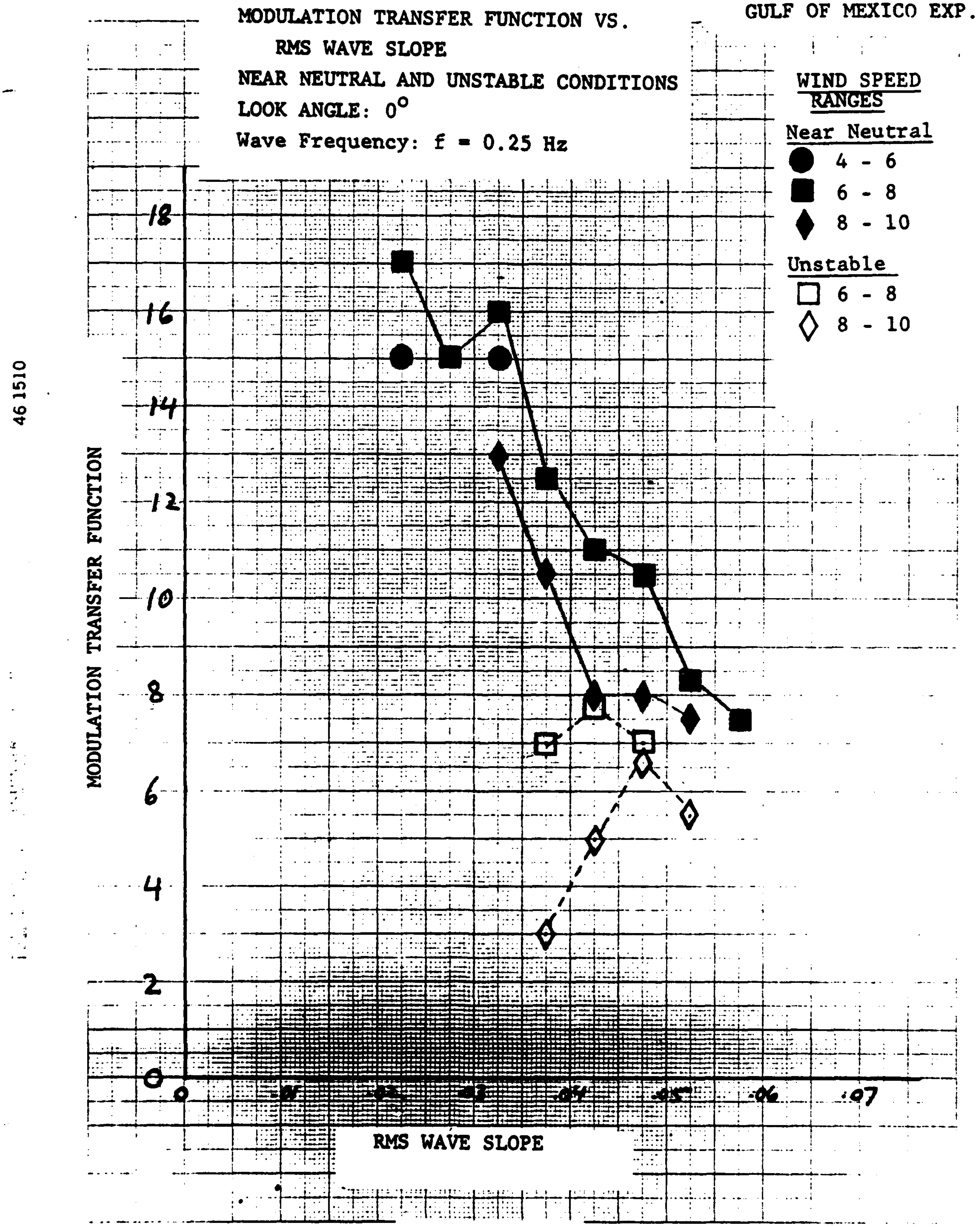
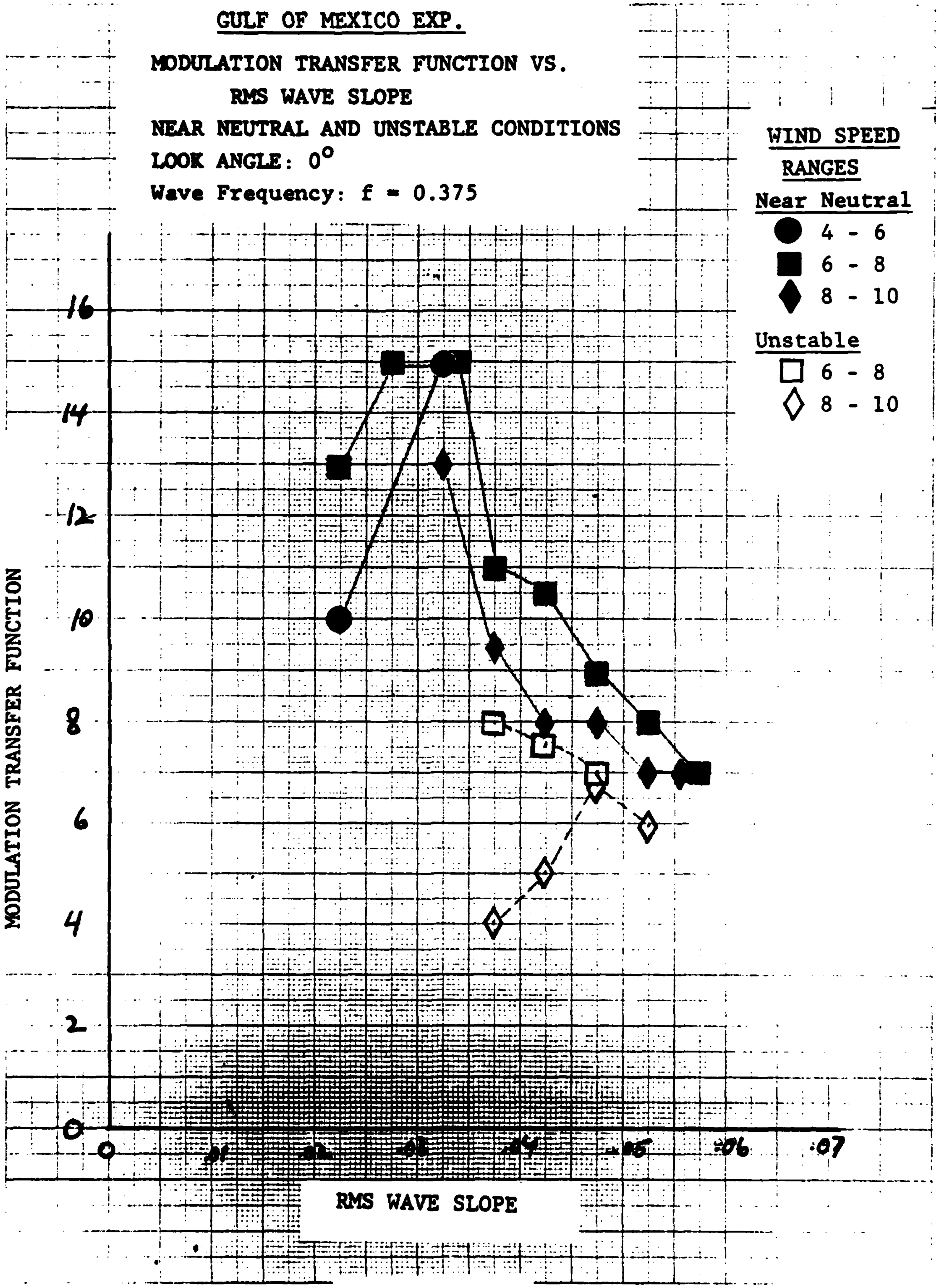

MODULATION TRANSFER FUNCTION VS.
RMS WAVE SLOPE
NEAR NEUTRAL AND UNSTABLE CONDITIONS
LOOK ANGLE: 0°
Wave Frequency: f = 0.25 Hz
GULF OF MEXICO EXP.
WIND SPEED RANGES
Near Neutral
4 - 6
6 - 8
8 - 10
Unstable
6 - 8
8 - 10
MODULATION TRANSFER FUNCTION
RMS WAVE SLOPE
18
16
14
12
10
8
6
4
2
0
0
.01
.02
.03
.04
.05
.06
.07
46 1510

Figure 5


GULF OF MEXICO EXP.
MODULATION TRANSFER FUNCTION VS.
RMS WAVE SLOPE
NEAR NEUTRAL AND UNSTABLE CONDITIONS
LOOK ANGLE: 0°
Wave Frequency: f = 0.375
WIND SPEED RANGES
Near Neutral
4 - 6
6 - 8
8 - 10
Unstable
6 - 8
8 - 10
MODULATION TRANSFER FUNCTION
16
14
12
10
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.07
RMS WAVE SLOPE

Figure 6

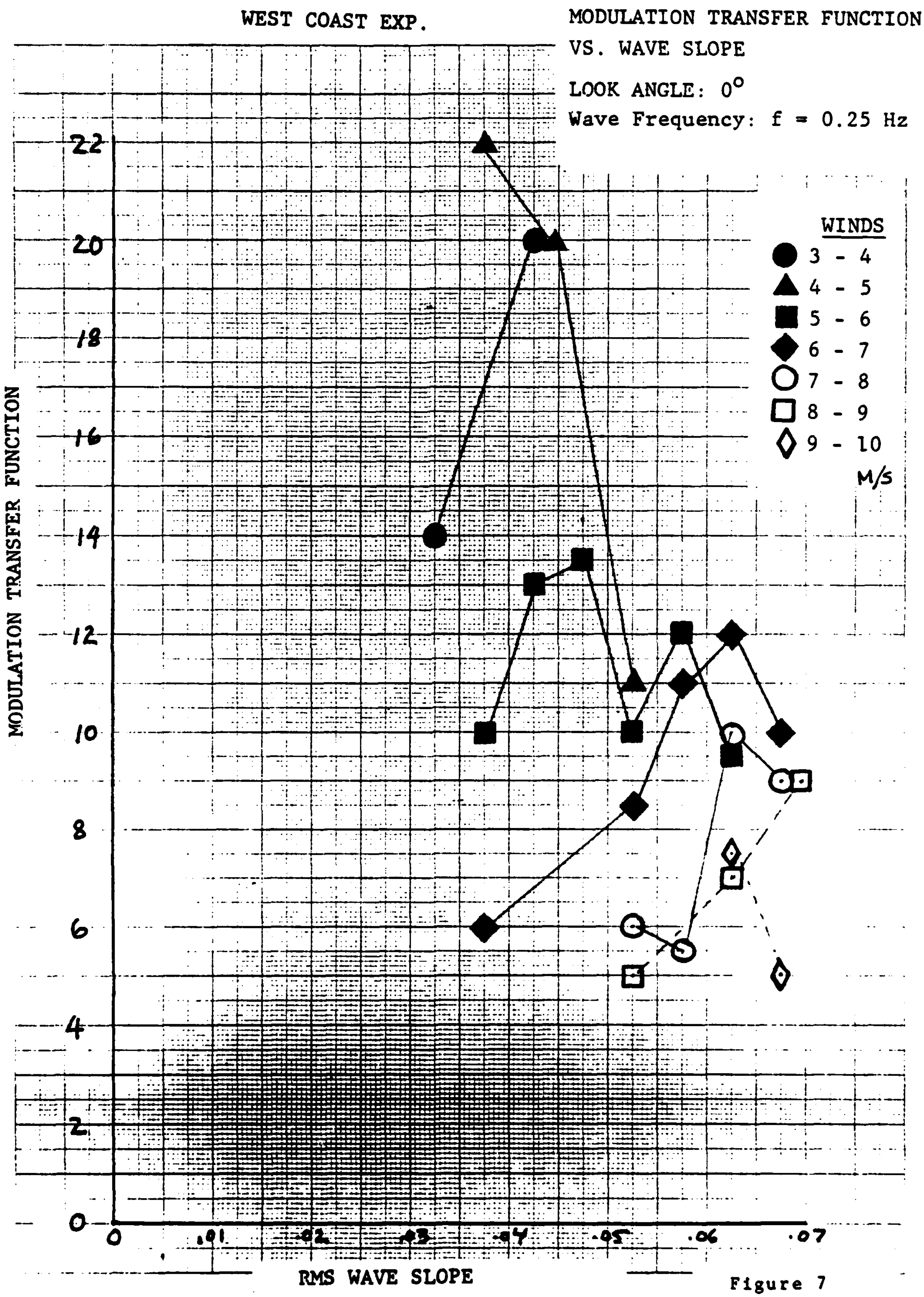

Figure 7

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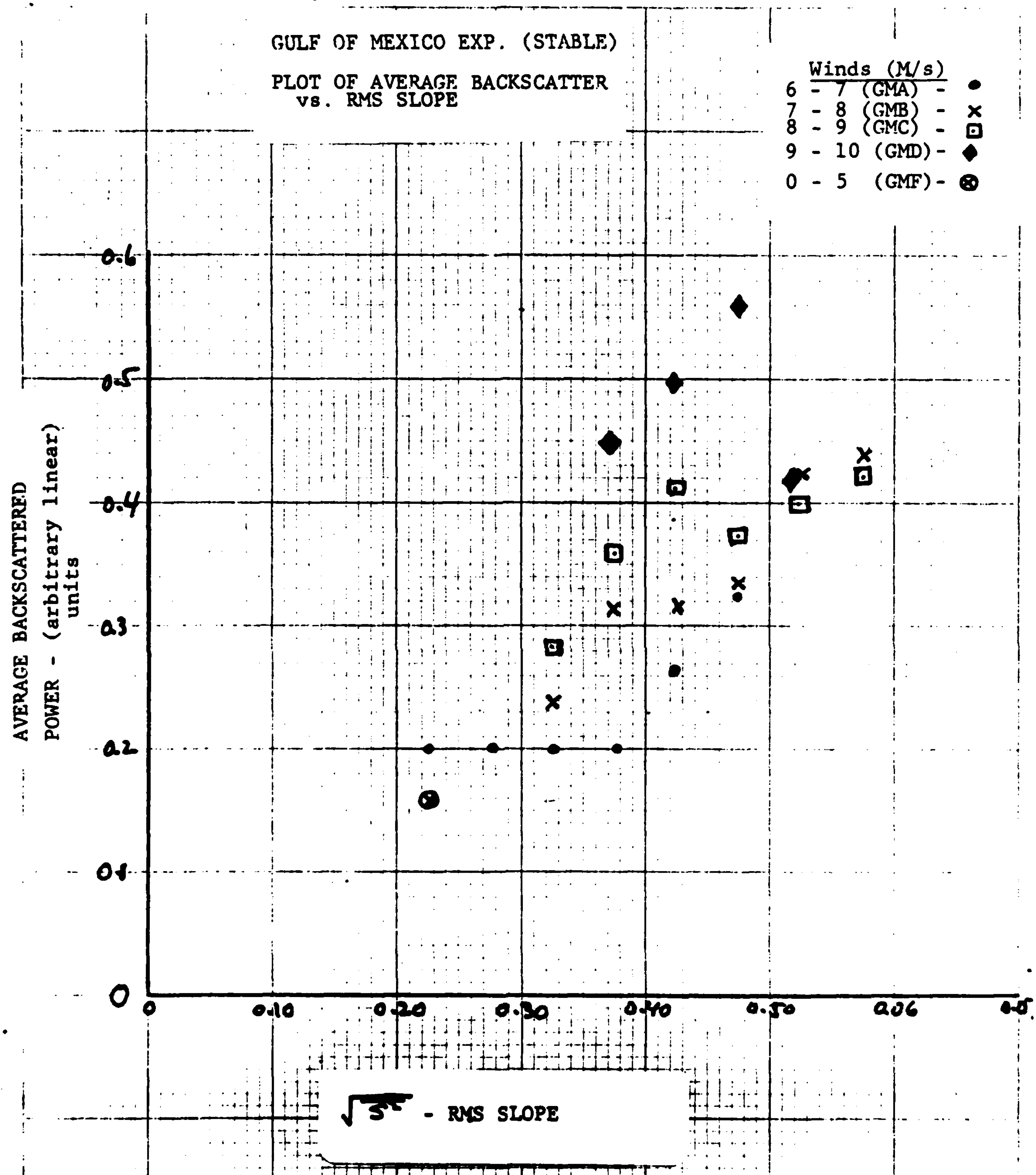
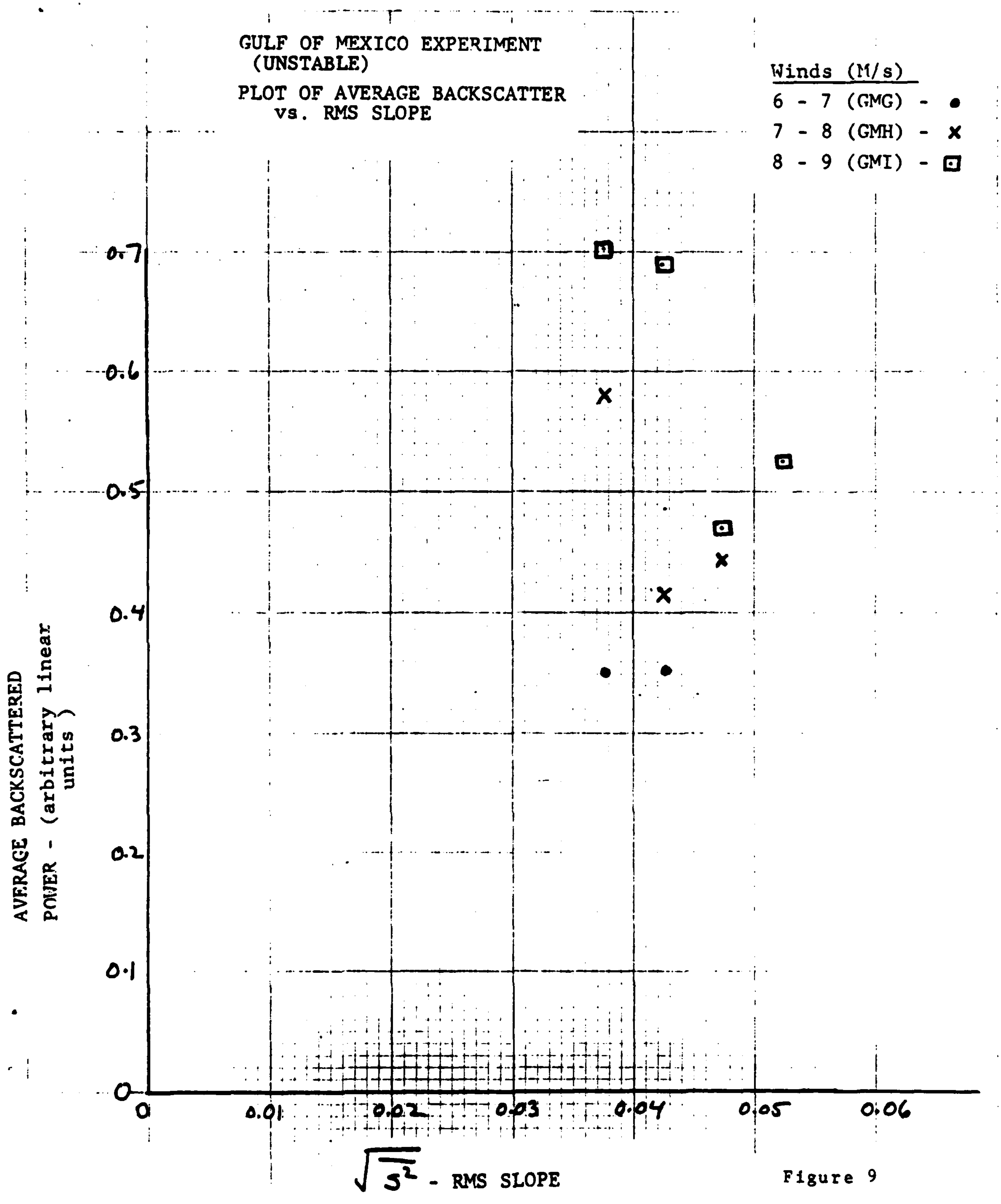

GULF OF MEXICO EXP. (STABLE)
PLOT OF AVERAGE BACKSCATTER vs. RMS SLOPE
Winds (M/s)
6 - 7 (GMA) -
7 - 8 (GMB) -
8 - 9 (GMC) -
9 - 10 (GMD) -
0 - 5 (GMF) -
AVERAGE BACKSCATTERED POWER - (arbitrary linear) units
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.10
0.20
0.30
0.40
0.50
0.06
0.6
- RMS SLOPE

Figure 8



GULF OF MEXICO EXPERIMENT
(UNSTABLE)
PLOT OF AVERAGE BACKSCATTER
vs. RMS SLOPE
Winds (M/s)
6 - 7 (GMG) - ●
7 - 8 (GMH) - ×
8 - 9 (GMI) - ⊡
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
AVERAGE BACKSCATTERED
POWER - (arbitrary linear
units)
0
0.01
0.02
0.03
0.04
0.05
0.06
$\sqrt{\overline{s^2}}$ - RMS SLOPE

Figure 9

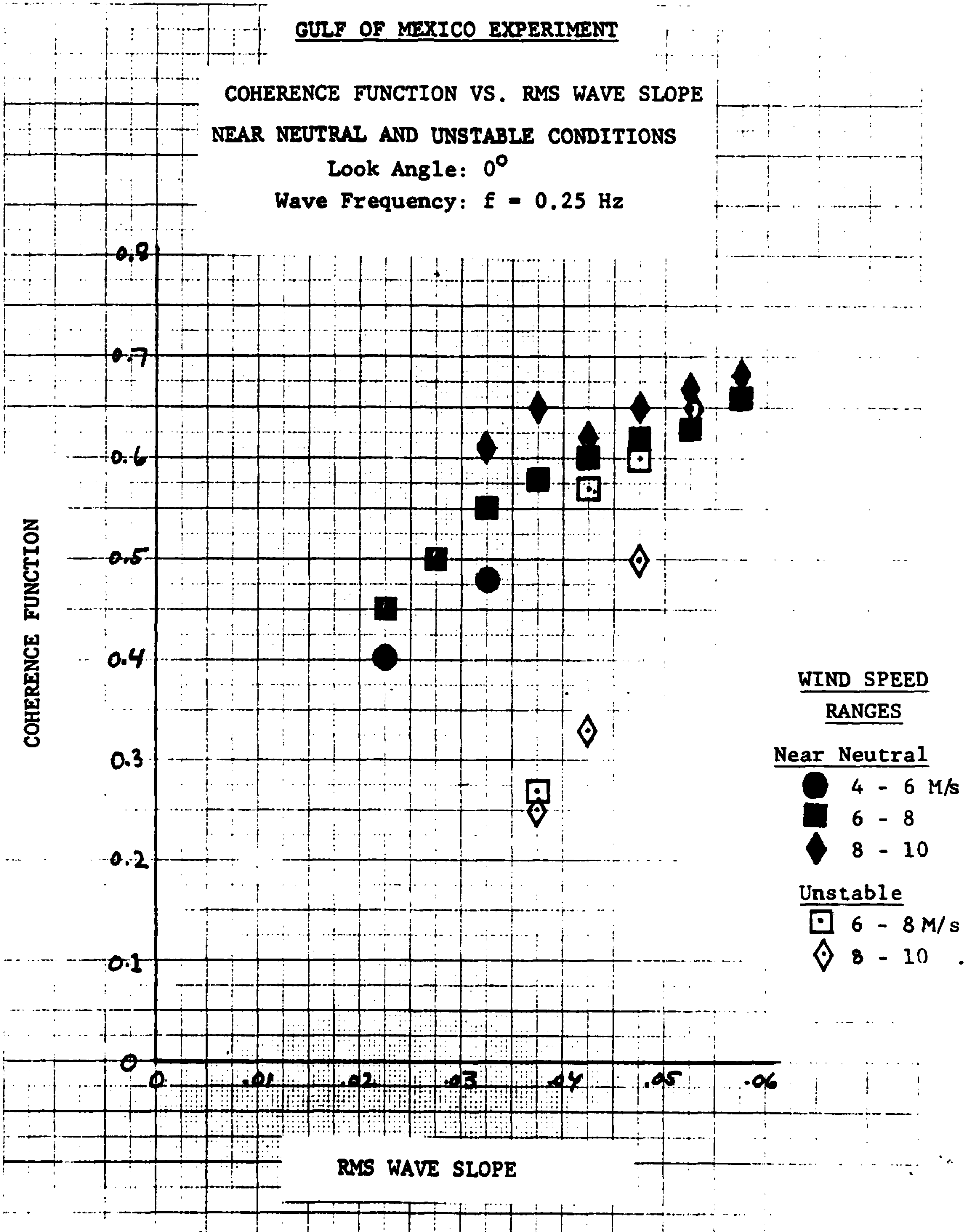


Figure 10

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END

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